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High-brightness LEDs—Energy efficient lighting sources and their potential in indoor plant cultivation

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ABSTRACT

The rapid development of optoelectronic technology since mid-1980 has significantly enhanced the brightness and efficiency of light-emitting diodes (LEDs). LEDs have long been proposed as a primary light source for space-based plant research chamber or bioregenerative life support systems. The raising cost of energy also makes the use of LEDs in commercial crop culture imminent. With their energy efficiency, LEDs have opened new perspectives for optimizing the energy conversion and the nutrient supply both on and off Earth. The potentials of LED as an effective light source for indoor agricultural production have been explored to a great extent. There are many researches that use LEDs to support plant growth in controlled environments such as plant tissue culture room and growth chamber. This paper provides a brief development history of LEDs and a broad base review on LED applications in indoor plant cultivation since 1990.

Contents

1. Introduction

With impacts of climate change, issues such as more frequent and serious droughts, floods, and storms as well as pest and diseases are becoming more serious threats to agriculture. These threats along with shortage of food supply make people turn to indoor and urban farming (such as vertical farming) for help. With proper lighting, indoor agriculture eliminates weather-related crop failures due to droughts and floods to provide year-round crop production, which assist in supplying food in cities with surging populations and in areas of severe environmental conditions.

The use of light-emitting diodes marks great advancements over existing indoor agricultural lighting. LEDs allow the control of spectral composition and the adjustment of light intensity to simulate the changes of sunlight intensity during the day. They have the ability to produce high light levels with low radiant heat output and maintain useful light output for years. LEDs do not contain electrodes and thus do not burn out like incandescent or fluorescent bulbs that must be periodically replaced. Not to mention that incandescent and fluorescent lamps consume a lot of electrical power while generating heat, which must be dispelled from closed environments such as spaceships and space stations.

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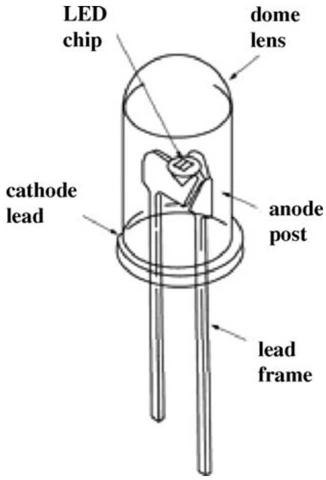

Fig. 1. The key structure of an LED.

2. LED development

LED is a unique type of semiconductor diode. It consists of a chip of semiconductor material doped with impurities to create a p–n junction. Current flows easily from the p-side (anode), to the n-side (cathode), but not in the reverse direction.

Electrons and holes flow into the junction from electrodes with different voltages. When an electron meets a hole, it falls into a lower energy level, and releases energy in the form of a photon. The color (wavelength) of the light emitted depends on the band gap energy of the materials forming the p–n junction. The materials used for an LED have a direct band gap with energies corresponding to near-infrared, visible or near-ultraviolet light.

The key structure of an LED consists of the die (or light-emitting semiconductor material), a lead frame where the die is placed, and the encapsulation which protects the die (Fig. 1).

LED development began with infrared and red devices made with gallium arsenide. Advances in materials science have made possible the production of devices with ever-shorter wavelengths, producing light in a variety of colors. J. Margolin [1] reported that the first known light-emitting solid state diode was made in 1907 by H. J. Round. No practical use of Round's diode was made for several decades until the invention of the first practical LED by Nick Holonyak, Jr in 1962. His LEDs became commercially available in late 1960s. These GaAsP LEDs combine three primary elements: gallium, arsenic and phosphorus to provide a 655 nm red light with brightness levels of approximately 1–10 mcd at 20 mA. As the luminous intensity was low, these LEDs were only used in a few applications, primarily as indicators. Following GaAsP, GaP (gallium phosphide) red LEDs were developed. These devices exhibit very high quantum efficiencies at low currents. As LED technology progressed through the 1970s, additional colors and wavelengths became available. The most common materials were GaP green and red, GaAsP orange, and high efficiency red and GaAsP yellow. The trend towards more practical applications (such as in calculators, digital watches, and test equipment) also began to develop. As the LED materials technology became more advanced, the light output was increased, and LEDs became bright enough to be used for illumination.

In 1980s a new material, GaAlAs (gallium aluminum arsenide) was developed followed by a rapid growth in the use of LEDs. GaAlAs technology provides superior performance over previously available LEDs. The voltage requirement is lower, which results in a total power savings. LEDs could be easily pulsed or multiplexed and thus are suitable for variable message and outdoor signs. Along this development period, LEDs were also designed into bar code scanners, fiber optic data transmission systems, and medical equipment. During this time, the improvements in crystal growth and optics design allow yellow, green and orange LEDs only a minor improvement in brightness and efficiency. The basic structure of the material remained relatively unchanged.

As laser diodes with output in the visible spectrum started to commercialize in late 1980s, LED designers used similar techniques to produce high-brightness and high reliability LEDs. This led to the development of InGaAlP (indium gallium aluminum phosphide) visible light LEDs. Via adjusting the energy band gap InGaAlP material can have different color output. Thus, green, yellow, orange and red LEDs could all be produced using the same basic technology. Also, light output degradation of InGaAlP material is significantly improved.

Shuji Nakamura at Nichia Chemical Industries of Japan introduced blue LEDs in 1993 [2]. Blue LEDs have always been difficult to manufacture because of their high photon energies (>2.5 eV) and relatively low eye sensitivity. Also, the technology to fabricate these LEDs is very different and less advanced than standard LED materials. But blue is one of the primary colors (the other two being red and green). Properly combining the red, green, and blue light is essential to produce white and full-color. This process requires sophisticated software and hardware design to implement. In addition, the brightness level is low and the overall light output of each RGB die being used degrades at a different rate resulting in an eventual color unbalance. The blue LEDs available today consist of GaN (gallium nitride) and SiC (silicon carbide) construction. The blue LED that becomes available in production quantities has result in an entire generation of new applications that include telecommunications products, automotive applications, traffic control devices, and full-color message boards. Even LED TVs can soon become commercially available.

Compare to incandescent light's 1000-h and fluorescent light's 8000-h life span, LEDs have a very significantly longer life of 100,000 h. In addition to their long life, LEDs have many advantages over conventional light source. These advantages include small size, specific wavelength, low thermal output, adjustable light intensity and quality, as well as high photoelectric conversion efficiency. Such advantages make LEDs perfect for supporting plant growth in controlled environment such as plant tissue culture room and growth chamber.

Table 1 is a list of some common types of LEDs as compiled from [3,4].

3. Color ratios and photosynthesis

The chlorophyll molecules in plants initiate photosynthesis by capturing light energy and converting it into chemical energy to help transforming water and carbon dioxide into the primary nutrient for living beings. The generalized equation for the photosynthetic process is given as:

$$CO_2 + H_2O \xrightarrow{\text{light}} (CH_2O) + O_2$$

Table 1
Some common types of LEDs.

Peak wavelength (nm)	Color	Material and structure of LEDs	Substrate
730	Far-red	GaAs	GaP
700	Red	GaP:Zn-O	GaP
660	Red	$GaAl_{0.35}As$	GaAs
650	Red	$GaAs_{0.6}P$	GaAs
630	Orange–red	$GaAs_{0.35}P_{0.65}$:N	GaP
610	Orange	$GaAs_{0.25}P_{0.75}$:N	GaP
590	Yellow	$GaAs_{0.15}P_{0.85}$:N	GaP
585	Yellow	$GaAs_{0.14}P_{0.86}$:N	GaAs
565	Green	GaP:N	GaP
450	Blue	GaN/SiC	–

where (CH_2O) is the chemical energy building block for the synthesis of plant components.

Chlorophyll molecules absorb blue and red wavelengths most efficiently. The green and yellow wavelengths are reflected or transmitted and thus are not as important in the photosynthetic process. That means limit the amount of color given to the plants and still have them grow as well as with white light. So, there is no need to devote energy to green light when energy costs are a concern, which is usually the case in space travel.

The LEDs enable researchers to eliminate other wavelengths found within normal white light, thus reducing the amount of energy required to power the plant growth lamps. The plants grow normally and taste the same as those raised in white light.

Red and blue light best drive photosynthetic metabolism. These light qualities are particularly efficient in improving the developmental characteristics associated with autotrophic growth habits. Nevertheless, photosynthetically inefficient light qualities also convey important environmental information to a developing plant. For example, far-red light reverses the effect of phytochromes, leading to changes in gene expression, plant architecture, and reproductive responses. In addition, photoperiod (the adjustment of light and dark periods) and light quality (the adjustment of red, blue and far-red light ratio) also have decisive impacts on photomorphogenesis.

The superimposed pattern of luminescence spectrum of blue LED (450–470 nm) and that of red LED (650–665 nm) corresponds well to light absorption spectrum of carotenoids and chlorophyll. Various plant cultivation experiments are possible when these two kinds of LED are used with the addition of far-red radiation (730–735 nm) as the light source. Along the line of the LED technology advancement, LEDs become a prominent light source for intensive plant culture systems and photobiological researches. The cultivation experiments which use such light sources are becoming increasingly active. Plant physiology and plant cultivation researches using LEDs started to peak in 1990s and become inevitable in the new millennium. Those researches have confirmed that LEDs are suitable for cultivation of a variety of algae, crop, flower, fruit, and vegetable.

Some of the pioneering researches are reviewed in the followings.

Bula et al. [5] have shown that growing lettuce with red LEDs in combination with blue *tubular fluorescent lamp* (TFL) is possible. Hoenecke et al. [6] have verified the necessity of blue photons for lettuce seedlings production by using red LEDs with blue TFL. As the price of both blue and red LEDs have dropped and the brightness increased significantly, the research findings have been able to be applied in commercial production. As reported by Agence France Press [7], Cosmo Plant Co., in Fukuroi, Japan has developed a red LED-based growth process that uses only 60% of electricity than a fluorescent lighting based one.

Tennessen et al. [8] have compared photosynthesis from leaves of kudzu (*Pueraria lobata*) enclosed in a leaf chamber illuminated by LEDs versus by a xenon arc lamp. The responses of photosynthesis to CO_2 are similar under the LED and xenon arc lamps at equal photosynthetic irradiance. There is no statistical significant difference between the white light and red light measurements in high CO_2. Some leaves exhibited feedback inhibition of photosynthesis which is equally evident under irradiation of either lamp type. The results suggest that photosynthesis research including electron transport, carbon metabolism and trace gas emission studies should benefit greatly from the increased reliability, repeatability and portability of a photosynthesis lamp based on LEDs.

Okamoto et al. [9] have investigated the effects of different ratios of red and blue (red/blue) *photosynthetic photon flux density* (PPFD) levels on the growth and morphogenesis of lettuce seedlings. They have found that the lettuce stem length decreases significantly with an increase in the blue PPFD. The research has also identified the respective PPFD ratio that (1) accelerates lettuce seedlings' stem elongation, (2) maximizes the whole plant dry weight, (3) accelerates the growth of whole plants, and (4) maximizes the dry weights of roots and stems.

Photosynthesis does not need to take place in continuous light. The solid state nature allows LEDs to produce sufficient photon fluxes and can be turned fully on and off rapidly (200 ns), which is not easily achievable with other light sources. This rapid on–off feature has made LEDs an excellent light source for photosynthesis research such as pulsed lighting for the study of photosynthetic electron transport details. The off/dark period means additional energy saving on top of the LEDs' low power consumption.

4. LEDs and indoor plant cultivation

4.1. Plant tissue culture and growth

Tissue culture (TC), used widely in plant science and a number of commercial applications, is the growth of plant tissues or cells within a controlled environment, an ideal growth environment that is free from the contamination of microorganisms and other contaminants. A controlled environment for PTC usually means filtered air, steady temperature, stable light sources, and specially formulated growth media (such as broth or agar). Micropropagation, a form of *plant tissue culture* (PTC), is used widely in forestry and floriculture. It is also used for conserving rare or endangered plant species. Other uses of PTC include:

- short-term testing of genetic constructions or regeneration of transgenic plants,
- cross breeding distantly related species and regeneration of the novel hybrid,
- screening cells for advantageous characters (e.g. herbicide resistance/tolerance),
- embryo rescue (i.e. to cross-pollinate distantly related species and then tissue culture the resulting embryo which would normally die),
- large-scale growth of plant cells in liquid culture inside bioreactors as a source of secondary products (like recombinant proteins used as biopharmaceuticals), and
- production of doubled monoploid plants from haploid cultures to achieve homozygous lines more rapidly in breeding programs (usually by treatment with colchicine which causes doubling of the chromosome number).

Tissue culture and growth room industries have long been using artificial light sources for production. These light sources include TFL, high pressure sodium lamp (HPS), metal halide lamp (MHL) and incandescent lamp, etc. Among them, TFL has been the most popular in tissue culture and growth room industries. However, the use of TFL consumes 65% of the total electricity in a tissue culture lab. That is the highest non-labor costs. As a result, these industries continuously seek for more efficient light sources. The development of high-brightness LED has made LED a promising light source for plant growth in controlled environments.

Nhut et al. [10] have cultured strawberry plantlets under different blue to red LED ratios as well as irradiation levels and compared its growth to that under plant growth fluorescent. The results suggest that a culture system using LED is advantageous for the micropropagation of strawberry plantlets. The study also demonstrates that the LED light source for *in vitro* culture of plantlets contributes to an improved growth of the plants in acclimatization.

Brown et al. [11] have measured the growth and dry matter partitioning of 'Hungarian Wax' pepper (*Capsicum annuum* L.) plants grown under red LEDs compared with similar plants grown under red LEDs with supplemental blue or far-red radiation. Pepper biomass reduces when grown under red LEDs without blue wavelengths compared to plants grown under supplemental blue fluorescent lamps. The addition of far-red radiation results in taller plants with greater stem mass than red LEDs alone. Fewer leaves developed under red or red plus far-red radiation than with lamps producing blue wavelengths. The results of their research indicate that with proper combination of other wavelengths, red LEDs may be suitable for the culture of plants in tightly controlled environments.

4.2. Space agriculture

Because re-supply is not an option, plants are the only options to generate enough food, water and oxygen to help make future explorers self-sufficient at space colonies on the moon, Mars or beyond. In order to use plants, there must be a light source. Standard light sources that used in homes and in greenhouses and in growth chambers for controlled agriculture here on Earth are not efficient enough for space travel. While a human expedition outside Earth orbit still might be years away, the space farming efforts are aimed at developing promising artificial light sources. LEDs, because of their safety, small mass and volume, wavelength specificity, and longevity, have long been proposed as a primary light source for space-base plant research chamber or bioregenerative life support systems [5,12].

Infrared LEDs that are used in remote controls devices have other uses. Johnson et al. [13] have irradiated oat (*Avena sativa cv Seger*) seedlings with infrared (IR) LED radiation passed through a visible-light-blocking filter. The irradiated seedlings exhibited differences in growth and gravitropic response when compared to seedlings grown in darkness at the same temperature. This suggests that the oat seedlings are able to detect IR LED radiation. These findings also expand the defined range of wavelengths involved in radiation–gravity (light–gravity) interactions to include wavelengths in the IR region of the spectrum.

Goins et al. [14] grow wheat under red LEDs and compare them to the wheat grown under (1) white fluorescent lamps and (2) red LEDs supplemented with blue light from blue fluorescent lamps. The results show that wheat grown under red LEDs alone displayed fewer subtillers and a lower seed yield compared to those grown under white light. Wheat grown under red LEDs + 10% BF light had comparable shoot dry matter accumulation and seed yield relative to those grown under white light. These results indicate that wheat can complete its life cycle under red LEDs alone, but larger plants and greater amounts of seed are produced in the presence of red LEDs supplemented with a quantity of blue light.

The research of Goins and his team continues in plant growth chambers the size of walk-in refrigerators with blue and red LEDs to grow salad plants such as lettuce and radishes. They hope the plant growth chamber would enable space station staff to grow and harvest salad greens, herbs and vegetables during typical four-month tours on the outpost [15].

4.3. Algaculture

Algaculture, refers to the farming of species of algae, has been a great source for feedstock, bioplastics, pharmaceuticals, algae fuel, pollution control, as well as dyes and colorants. Algaculture also provides hopeful future food sources.

Algae can be grown in a *photobioreactor* (PBR), a bioreactor which incorporates some type of light source. A PBR is a closed system, as opposed to an open tank or pond. All essential nutrients must be introduced into the system to allow algae to grow and be cultivated. A PBR extends the growing season and allows growing more species. The device also allows the chosen species to stay dominant. A PBR can either be operated in "batch mode" or "continuous mode" in which a continuous stream of sterilized water that contains air, nutrients, and carbon dioxide is introduced. As the algae grows, excess culture overflows and is harvested.

When the algae grow and multiply, they become so dense that they block light from reaching deeper into the water. As a result, light only penetrates the top 7–10 cm of the water in most algal-cultivation systems. Algae only need about 1/10 the amount of direct sunlight. So, direct sunlight is often too strong for algae. A means of supplying light to algae at the right concentration is to place the light source in the system directly.

Matthijs et al. [16] have used LEDs as the sole light source in continuous culture of the green alga (*Chlorella pyrenoidosa*). The research found the light output of the LED panel in continuous operation sufficient to support maximal growth. Flash operation at 5-ps pulse "on" duration between dark periods of up to 45 ps would still sustain near maximum growth. While longer dark periods tend to cut the growth rate, the light flux decrease resulting from such operation does not reduce the growth as much as that of the similar flux decrease in continuous operation. Their research concludes that the use of flashing LEDs (which means intermittent light) in indoor algal culture yielded a major gain in energy economy comparing to fluorescent light sources. An additional advantage is that heat waste losses are much smaller. The most interesting discovery of this study may be that adding blue light to the red LED light did not change the growth properties.

In order to take advantage of the biotechnological potential of algae, Lee and Palsson [17] have calculated theoretical values of gas mass transfer requirements and light intensity requirements to support high-density algal cultures for the 680 nm monochromatic red light from LED as a light source. They have also designed a prototype PBR based on these calculations. Using on-line ultra filtration to periodically provide fresh medium, these researchers have achieved a cell concentration of more than 2×10^9 cells/ml (more than 6.6%, vol/vol), cell doubling times as low as 12 h, and an oxygen production rate as high as 10 mmol oxygen/l culture/h. This research indicates that the development of a small LED-based algal photobioreactors is economically achievable.

Another research of algae via LEDs is conducted by Nedbal et al. [18]. Their research is a study of light fluctuation effects on a variety of algae in dilute cultures using arrays of red LEDs to provide intermittent and equivalent continuous light in small-size (30 ml) bioreactors. The results endorse that the algae growth rates in certain calculated intermittent light can be higher than the growth rate in the equivalent continuous light.

Yanagi and Okamoto [19] has grown five spinach plants under the red LEDs and another five under 40 W plant growth fluorescent lamps at the same light intensity of 125 μmol/m^2/s. The dry matter production under the LEDs is slightly less than that under the fluorescent lamps. The plant leaf area under the red LEDs is also smaller than that under the fluorescent lamps. Nevertheless, they reach a conclusion that LEDs can qualify as an artificial light source for plant growth.

4.4. Plant disease reduction

Schuerger and Brown [20] have used LED arrays with different spectral qualities to determine the effects of light on the development of tomato mosaic virus (ToMV) in peppers and powdery mildew on cucumbers. Their research concludes that spectral quality may alter plant disease development. Latter research [21] regarding bacterial wilt on tomato has confirmed this

conclusion and demonstrates that spectral quality may be useful as a component of an integrated pest management program for space-based ecological life support systems. Schuerger et al. [22] have shown that the spectral quality effects on peppers' anatomical changes in stem and leaf tissues are correlated to the amount of blue light in primary light source.

Miyashita et al. [23] use red LEDs (peak wavelength: 660 nm) and white fluorescent lamps as light sources for potato plantlets growth *in vitro*. They found that shoot length and chlorophyll concentration of the plantlets increases with increasing 630–690 nm red photon flux (R-PF) while there are no significant differences in dry weight and leaf area of the plantlets with different R-PF levels. This means red light affects the morphology rather than the growth rate of potato plantlets *in vitro*. As a result, they suggest that red LEDs can be used for controlling plantlet morphology in micropropagation.

5. Intermittent and photoperiod lighting and energy saving

Time constants for photosynthetic processes can be divided into three ranges: primary photochemistry, electron shuttling, and carbon metabolism. These three photosynthetic processes can be uncoupled by providing pulses of light within the appropriate range for each process. At high frequencies, pulsing light treatments can be used to separate the light reactions (light harvesting and charge separation) from the dark reactions (electron shuttling) of photosynthetic electron transport. LEDs' flexible pulsating ability can be coupled with such characteristics of photosynthesis and lead to additional energy saving.

Tennessen et al. [24] use LEDs to study the effects of light pulses (micro- to milli-second) of intact tomato leaves. They found that when the equivalent of 50 μmol photons $mp^{-2}\,s^{-1}$ is provided during 1.5 μs pulses of 5000 μmol photons $mp^{-2}\,s^{-1}$ followed by 148.5 μs dark periods, photosynthesis is the same as in continuous 50 μmol photons $mp^{-2}\,s^{-1}$. Data support the theory that photons in pulses of 100 ps or shorter are absorbed and stored in the reaction centers to be used in electron transport during the dark period. Pigments of the xanthophyll cycle were not affected by pulsed light treatments. This research suggests that, instead of continuous light, using effectively calculated intermittent light (which means less energy consumption) might not affect the plant production.

Jao and Fang [25] have investigated the effects of intermittent light on growth of potato plantlets *in vitro*. They also use conventional TFLs for the experiment to explore the electrical savings realized by adjusting the frequency and duty ratio of LEDs. TFLs provide continuous fluctuating light at 60 Hz while LEDs provide nonfluctuating light and pulse light of the preset frequency and duty ratio. When the growth rate is the only concern, LEDs at 720 Hz (1.4 ms) and 50% duty ratio with 16-h light/8-h dark photoperiod stimulated plant growth the most. When energy consumption is the major concern, using LEDs at 180 Hz (5.5 ms) and 50% duty ratio with 16-h light/8-h dark photoperiod would not significantly sacrifice plant growth, especially when energy for heat removal is also taken into account.

6. Conclusions

The first sustained work with LEDs as a source of plant lighting occurred in the mid-1980s when a lighting system for plant growth was designed for space shuttles and space stations for it is realized that people cannot go to the Moon, Mars, or beyond without first mastering the art of indoor farming on Earth. As the performance of LED continues to improve, these lighting systems progress from red only LED arrays using the limited components available to high-density, multi-color LED chip-on-board technologies. Today, space age gardeners who have been testing high-efficiency light sources for future space colonists have identified energy efficient LEDs as the major light source not only to grow food but also to generate and purify oxygen and water—key sustainers of human life. The removal of carbon dioxide from a closed environment is another added benefit.

LEDs are the first light source to provide the capability of true spectral composition control, allowing wavelengths to match to plant photoreceptors to optimize production as well as to influence plant morphology and composition. They are easily integrated into digital control systems, facilitating complex lighting programs like varying spectral composition over the course of a photoperiod or with plant development stage. LEDs do not contain mercury. They are safer to operate than current lamps since they do not have glass envelopes or high touch temperatures.

While the process of photosynthesis does not require continuous light of full spectrum, LEDs can produce sufficient photon fluxes of specific wavelength on and off rapidly. Such mechanism of photosynthesis coupled with the solid state characteristics of LEDs constitute two ways of energy saving (cutting out unnecessary spectrum segment and turning off the light periodically) on top of the LEDs' low power consumption. These are not easily achievable with other light sources.

This paper provides a broad base review on LED applications in horticulture industry since 1990. These researches pave the way for the researches of similar types using different species and lead to comparable conclusion that LEDs are well qualified to replace its more energy demanding counterparts as controlled environment light source for agricultural research such as providing tissue culture lighting as well as supplemental and photoperiod lighting for greenhouses.

With the energy it can save, LED's becoming economically feasible in large-scale indoor farming lighting applications is just around the corner.

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